

****Volume Title****

*ASP Conference Series, Vol. **Volume Number***

****Author****

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The Evolution of Cataclysmic Variables

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Abstract. I review our current understanding of the evolution of cataclysmic variables (CVs). I first provide a brief introductory “CV primer”, in which I describe the physical structure of CVs, as well as their astrophysical significance. The main part of the review is divided into three parts. The first part outlines the theoretical principles of CV evolution, focusing specifically on the standard “disrupted magnetic braking” model. The second part describes how some of the most fundamental predictions this model are at last being test observationally. Finally, the third part describes recent efforts to actually reconstruct the evolution path of CVs empirically. Some of these efforts suggest that angular momentum loss below the period gap must be enhanced relative to the purely gravitational-radiation-driven losses assumed in the standard model.

1. Introduction: A CV Primer

Cataclysmic Variables (CVs) are binary systems containing an accreting white dwarf (WD). However, this broad class also contains other types of objects, so the taxonomy may be a little confusing. Figure 1 therefore provides a simplified take on how CVs fit into the zoo of accreting WDs. The key point is that the secondaries in CVs are stars on or near the main sequence (MS). In fact, for the purpose of this review, I will focus almost exclusively on CVs in which the secondaries have undergone no significant nuclear evolution at the onset of mass transfer. These dominate the CV population below $P_{orb} \simeq 4 - 5$ hr (Beuermann et al. 1998; Podsiadlowski et al. 2003; Knigge 2006). In fact, I will further concentrate on *non-magnetic* CVs, i.e. systems in which the magnetic field of the primary WD is too weak to affect the accretion flow. This restriction matters, since the much rarer magnetic CVs may evolve differently from non-magnetic ones (e.g. Wu et al. 1995; Townsley & Gänsicke 2009).

The physical structure of non-magnetic CVs is illustrated in Figure 2. CVs are *close* binary systems, with binary separations $a_{bin} \sim R_{\odot}$ and orbital periods $80 \text{ min} \lesssim P_{orb} \lesssim 6 \text{ hr}$. As a result, the secondary undergoes Roche-lobe overflow and loses mass through the inner Lagrangian point. Since this material has excess angular momentum, it is then transported towards the WD via an accretion disk.

The mass transfer process in CVs appears to be relatively stable on long time scales. This requires both that the mass ratio $q = M_2/M_1 \lesssim 1$ and also the existence of an angular momentum loss (AML) process that continually shrinks the system and thus keeps the Roche lobe in touch with the secondary star. The orbital period therefore initially decreases as a CV evolves, making the period distribution a powerful tracer of CV evolution. Figure 3 shows this period distribution for CVs. The two most obvious

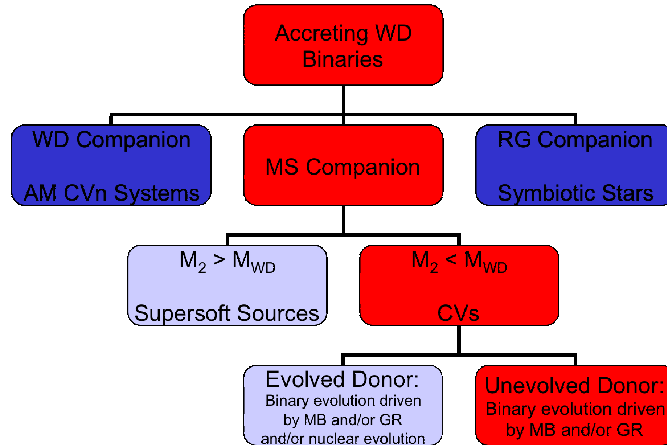


Figure 1. The taxonomy of accreting white dwarf binary systems.

features in this distribution are (i) the famous “period gap” between $P_{orb} \simeq 2$ hr and $P_{orb} \simeq 3$ hr; (ii) a sharp cut-off around a minimum period of $P_{min} \simeq 80$ min.

In what has become the “standard model” for CV evolution, mass transfer *above* the gap is driven primarily by AMLs associated with a weak, magnetized stellar wind from the secondary (“magnetic braking” [MB]), while mass transfer *below* the gap is driven solely by gravitational radiation (GR). As we shall see in more detail below, the period gap then arises as a consequence of the cessation of MB at $P_{orb} \simeq 3$ hr. It is usually assumed that this cessation is associated with the transition of the star from a partly radiative structure to a fully convective one. The period minimum is also associated with a change in the structure of the donor. Roughly speaking (see below), P_{min} marks the transition of the donor from a star to a sub-stellar object. Since the radius of a brown dwarf *increases* in response to mass loss, this transition must also lead to a change in the direction of orbital period evolution. Systems that have already evolved *beyond* P_{min} are often referred to as “period bouncers”.

Understanding the evolution of CVs – in the first instance by testing this standard model – is astrophysically important. This is illustrated in Figure 4, which places CVs in the context of other close binary systems. First, even though many binary stars interact with each other at some stage of their lives, CVs provide a rare opportunity to observe *long-lived stable* mass transfer in action. Second, the physical processes that are relevant to CV evolution – not just MB and GR, but also the infamous “common envelope” (CE) phase that brings these systems into (or close to) contact – are also key to many other types of binary systems. Third, some CVs and their relatives (such as the supersoft sources, see Figure 1) are expected to be Type Ia supernova progenitors. Fourth and finally, it is becomingly increasingly clear that most aspects of the accretion process in neutron star and black hole binary systems – including variability (e.g. Warner & Woudt 2005), accretion disk winds (Cordova & Mason 1982; Long & Knigge 2002, e.g.), and jets K rding et al. (2008) – have direct counterparts in CVs. Since CVs are relatively numerous, nearby, bright and characterized by observationally “convenient” orbital time-scales, this makes them extremely useful as laboratories for the study of accretion onto compact objects more generally.

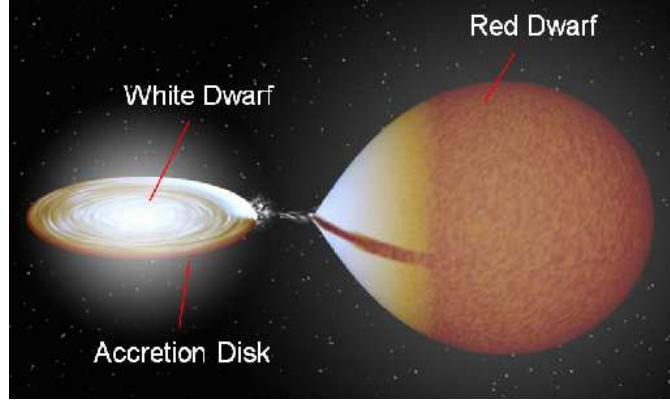


Figure 2. The physical structure of CVs. The key components are a roughly MS Roche-lobe-filling secondary star, an accreting WD primary, and an accretion disk surrounding the WD. This figure was created by Rob Hynes using his BinSim binary visualization code (see <http://www.phys.lsu.edu/~rih/binsim>).

2. Principles of CV Evolution: Theory

The evolution of CVs is closely connected to – and in some sense controlled by – the properties of their secondary stars. Indeed, as noted above, mass transfer above the period gap is driven by MB (a process associated with the secondary), and both the period gap and the period minimum are thought to mark structural changes in the secondary. In order to understand CV evolution, we must therefore understand the properties of their donor stars. Much of the following is therefore reproduced from Knigge (2011), which reviews our current understanding of CV secondaries.

2.1. Fundamentals

The radius of a Roche-lobe-filling star depends only the binary separation, a , and the mass ratio, $q = M_2/M_1$. A particularly convenient approximation for the Roche-lobe radius is (Paczynski 1971)

$$\frac{R_L}{a} = \frac{2}{3^{4/3}} \left[\frac{q}{1+q} \right]^{1/3}, \quad (1)$$

which can be combined with Kepler's third law

$$P_{orb}^2 = \frac{4\pi^2 a^3}{G(M_1 + M_2)} \quad (2)$$

to yield the well-known *period-density relation* for Roche-lobe-filling stars with $R_2 = R_L$

$$\langle \rho_2 \rangle = \frac{M_2}{(4\pi/3)R_2^3} \simeq 100 G^{-1} P_{orb}^{-2}. \quad (3)$$

Let us assume for the moment that CV donors are indeed mostly low-mass, near-MS stars. We then expect that their mass-radius relationship will be roughly

$$R_2/R_\odot = f(M_2/M_\odot)^\alpha \quad (4)$$

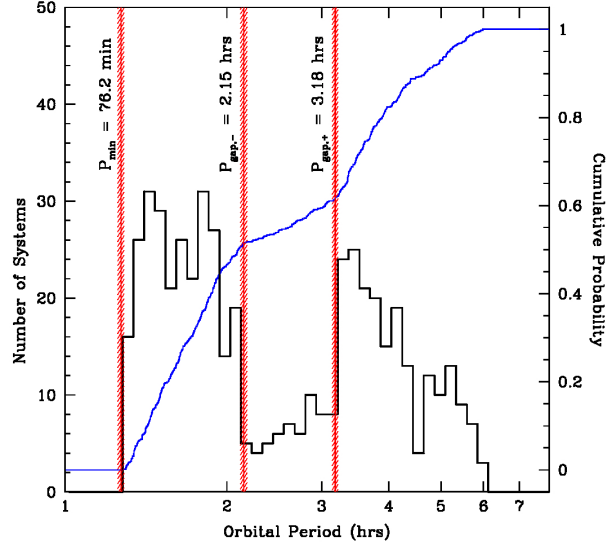


Figure 3. Differential and cumulative orbital period distribution of CVs, based on data taken from Edition 7.6 of the Ritter & Kolb catalogue (Ritter & Kolb 2003). Estimated values for the minimum period and the period gap edges are shown as vertical lines. The shaded regions around them indicate our estimate of the errors on these values. Figure reproduced from Knigge (2006).

with $f \approx \alpha \approx 1$. Combining this with the period-density relation immediately gives approximate mass-period and radius-period relations for CV donors

$$M_2/M_\odot = M_2/M_\odot \approx 0.1P_{orb,hr}, \quad (5)$$

where $P_{orb,hr}$ is the orbital period in units of hours. This shows that the period gap between 2 hrs and 3 hrs corresponds to $M_2 \approx 0.2 - 0.3M_\odot$, which is, in fact, where the secondary is expected to change structure from partly radiative to fully convective.

2.2. Are CV Donors on the Main Sequence?

How good is the assumption that CV donors are nearly ordinary MS stars? The answer depends on the competition between the mass-loss time scale, on which the ongoing mass transfer reduces the donor mass,

$$\tau_{M_2} \approx \frac{M_2}{\dot{M}_2}. \quad (6)$$

and the thermal time scale, on which the donor can correct deviations from thermal equilibrium (TE),

$$\tau_{th} \approx \frac{GM_2^2}{L_2 R_2} \approx 10^8 (M_2/M_\odot)^{-3/2} \text{yrs}. \quad (7)$$

If mass loss is slow, in the sense that $\tau_{M_2} \gg \tau_{th}$, the donor always has time to adjust itself to attain the appropriate TE structure for its current mass. It therefore remains

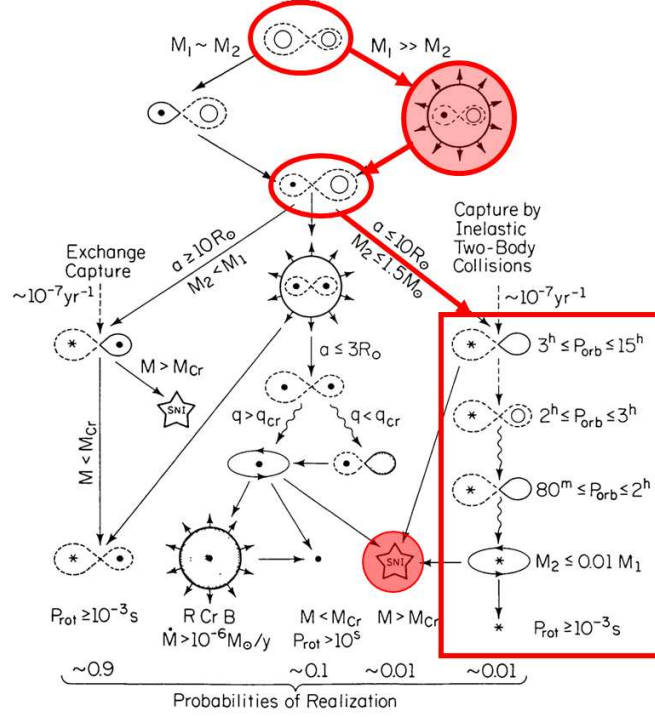


Figure 4. Basic scenarios for binary star evolution after Iben (1991) and Iben & Tutukov (1984). Rings are unevolved stars; filled circles are electron-degenerate helium, carbon-oxygen, or oxygen-neon cores in giants; six-pointed stars are white dwarfs or neutron stars. Wavy lines mark transitions driven by the radiation of gravitational waves and counter-clockwise rotating ellipses are heavy disks. Open stars represent Type Ia supernova explosions. Roche lobes are shown by dashed loops (when not filled) or by solid loops (when filled). The probability of realization of different final products is indicated at the bottom of the figure. The evolutionary channel marked in red is that expected to produce most CVs. The CV phase itself is marked by the red box. Figure adapted from Iben (1991).

on the MS, with a mass-radius index $\alpha \simeq 1$, and is essentially indistinguishable from an isolated MS star. Conversely, if mass loss is fast, i.e. $\tau_{\dot{M}_2} \ll \tau_{th}$, the donor cannot adjust its structure quickly enough to remain in TE. Instead, the mass loss is effectively adiabatic. The response of low-mass stars with at least a substantial convective envelope to such mass loss is to *expand*, with $\alpha \simeq -1/3$.

Which of these limits is appropriate for CVs? Neither, as it turns out. Let us take some typical parameters suggested by the standard model for CVs above and below the gap, say $M_2 \simeq 0.4$ with $\dot{M}_2 \simeq 1 \times 10^{-9}$ and $M_2 \simeq 0.1$ with $\dot{M}_2 \simeq 3 \times 10^{-11}$, respectively. Plugging these values into Equations 6 and 7, we find $\tau_{\dot{M}_2} \simeq \tau_{th} \simeq 4 \times 10^8$ yrs above the gap and $\tau_{\dot{M}_2} \simeq \tau_{th} \simeq 3 \times 10^9$ yrs below. *Thus the thermal and mass-loss time scales are comparable for CV donors, both above and below the period gap.*

What this means is that the donor cannot *quite* shrink fast enough to keep up with the rate at which mass is removed from its surface. It is therefore driven slightly out

of thermal equilibrium and becomes somewhat oversized for its mass. It is this slight deviation from TE that ultimately explains both the period gap and the period minimum.

2.3. The Origin of the Period Gap

Let us take as given, for the moment, that the period gap is “somehow” associated with a sudden cessation of (or at least reduction in) MB a $P_{orb} \simeq 3$ hrs. Why should this produce a period gap in the CV population?

Recall that the donor star is slightly out of thermal equilibrium – i.e. slightly bloated – as it encounters the upper edge of the period gap. Now, since mass transfer in CVs is driven entirely by AML, a sudden reduction in AML will also result in a sudden reduction in the mass-loss rate the donor experiences. This lower mass-loss rate cannot sustain the same degree of thermal disequilibrium and inflation in the secondary star. The donor therefore responds to this change by shrinking closer to its thermal equilibrium radius. This results in a loss of contact with the Roche lobe.

The upper edge of the gap thus marks a cessation of mass transfer in CVs. According to the standard model, CVs then evolve through the period gap as detached systems. During this detached phase, the binary orbit and Roche lobe continue to shrink, since AML due to GR continues. However, since the thermal relaxation of the donor in this phase is faster than the shrinkage of the Roche lobe, the donor manages to relax all the way back to its TE radius. The bottom edge of the period gap thus corresponds to the location where the Roche lobe radius catches up once again to the TE radius of the donor. At this point, mass transfer restarts, and the system emerges from the gap as an active CV once again.

How bloated must CV donors be to account for the observed size of the period gap? Since there is no mass transfer *in* the gap, the donor mass just above and below the gap must be the same, $M_2(P_{gap,+}) = M_2(P_{gap,-})$. From the period-density relation (Equation 3), we then get

$$\frac{R_2(P_{gap,+})}{R_2(P_{gap,-})} = \left[\frac{P_{gap,+}}{P_{gap,-}} \right]^{2/3} \simeq \left[\frac{3}{2} \right]^{2/3} \simeq 1.3. \quad (8)$$

We also know that the donor at the bottom edge is in or near equilibrium, so that *donors at the upper edge of the period gap must be oversized by $\simeq 30\%$ relative to equal-mass, isolated MS stars.*

2.4. The Origin of the Period Minimum

The period minimum is also closely connected to the properties of the donor stars. If we combine the period-density relation (Equation 3) with the simple power-law approximation to the donor mass-radius relation (Equation 4), we find

$$P_{orb}^{-2} \propto M_2^{1-3\alpha}. \quad (9)$$

Differentiating this logarithmically yields a simple expression for the orbital period derivative, i.e.

$$\frac{\dot{P}_{orb}}{P_{orb}} = \frac{3\alpha - 1}{2} \frac{\dot{M}_2}{M_2}. \quad (10)$$

Since the period minimum must correspond to $\dot{P}_{orb} = 0$, Equation 10 tells us that P_{min} occurs when the donor has been driven so far out of thermal equilibrium that its

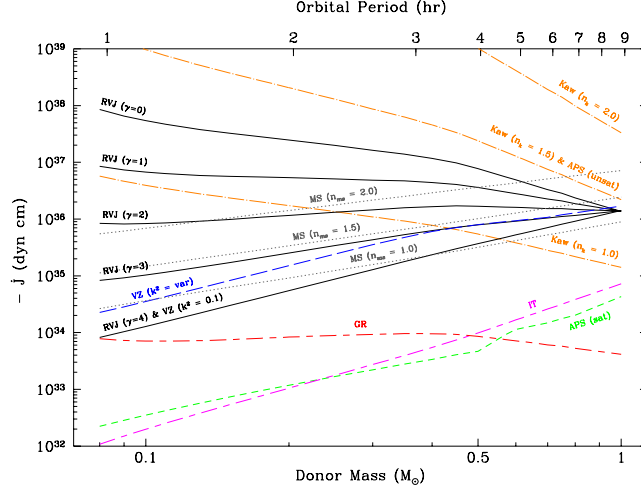


Figure 5. A comparison of several widely used angular momentum loss recipes. The red long-dash-short-dash line corresponds to GR-driven AML; the blue long-dashed lines the classic Verbunt & Zwaan (1981) prescription; the solid black lines mark the Rappaport et al. (1983) prescription; the orange dash-dotted line mark the Kawaler (1988) recipe; the gray dotted lines mark the Mestel & Spruit (1987) law; the green short-dashed line shows the saturated model suggested by Andronov et al. (2003); long-dashed magenta line shows the saturated AML law suggested by Ivanova & Taam (2003). For several recipes, several versions with different parameters are shown. The main thing to take away from this figure is the enormous range in shapes and strengths, even for conceptually similar AML prescriptions. Figure reproduced from Knigge et al. (2011), which also provides more details on the various AML recipes.

mass-radius index along the evolution track has been reduced from its near-MS value of $\alpha \simeq 1$ to $\alpha = 1/3$. So, as already noted above, P_{min} does not necessarily have to coincide with the orbital period at which the donor mass reaches the Hydrogen-burning limit, M_H . In fact, recall that we noted in Section 2.2 that, for any donor with at least a substantial convective envelope, the mass-radius index in the limit of *fast* (adiabatic) mass-transfer is $\alpha \simeq -1/3$. Thus the period evolution of a CV can in principle be made to turn around at *any* donor mass, provided only that mass loss becomes sufficiently fast compared to the donor's thermal time scale. The significance of M_H in this context is that period bounce becomes inevitable when the donor reaches this limit. This is because sub-stellar objects are out of TE by definition and respond even to slow mass loss by increasing in radius, i.e. $\alpha \leq 0$. In practice, P_{min} does, in fact, correspond roughly to $M_2 \simeq M_H$.

2.5. Magnetic Braking

As noted above, stable mass transfer in CVs *requires* AML from the system, so understanding the process(es) by which this happens is key to understanding CV evolution. There is no great mystery about GR, of course, which (in the standard model) is thought to dominate below the period gap. However, how well do we really understand MB, the

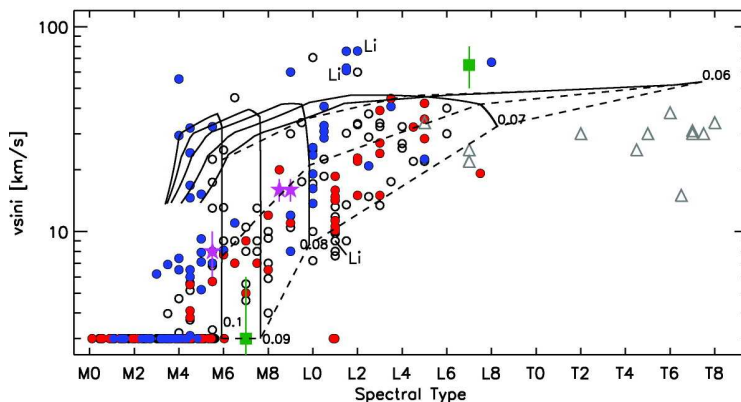


Figure 6. Measurements of $v \sin i$ for single stars. Filled blue circles are probably young, filled red circles old. The meaning of the remaining symbols and colours is not relevant to the discussion here. The solid lines mark evolutionary tracks for objects of 0.1, 0.09, 0.08, and 0.07 Modot; dashed lines mark ages of 2, 5, and 10 Gyr (from upper left to lower right). Figure adapted from Reiners & Basri (2008).

process expected to dominate above the gap, whose cessation is thought to *cause* the gap?

Figure 2.5, taken from Knigge et al. (2011), is an attempt to answer this question. For this figure, we compiled a variety of widely used MB recipes from the literature and compared the AML rates they predict for CV donors. In order to translate the predictions into orbital period space, we made the “marginal contact” approximation, i.e. we assumed CV secondaries follow the standard MS mass-radius relation and then used the period-density relation to estimate P_{orb} . For reference, we also extrapolated the predicted AML recipes into the fully convective regime.

A detailed discussion of the various MB prescriptions shown in Figure 2.5 is given in Knigge et al. (2011). However, the basic message is clear: there are huge differences between different recipes, not just in the rates they predict at fixed P_{orb} , but even in the *shape* of the AML rates they predict as a function of P_{orb} . To make matters worse, it has long been known that fully convective single stars manage to sustain significant magnetic fields, the key physical requirement for MB.

Does this mean that the whole idea of disrupted MB as a key driver of CV is without any basis? Not quite. Figure 2.5 shows the rotation velocities of single MS stars as a function of spectral type (Reiners & Basri (2008)). What is striking here is that all stars earlier than about M5 are extremely slow rotators, whereas stars later than about M5 are characterized by a wide range of higher rotation rates. Now this spectral type – M5 – actually corresponds roughly to the dividing line between fully convective and partly radiative stars. So there is actually some empirical evidence that mass-losing stars may experience a reduction (if not necessarily a complete cessation) in MB as they cross this dividing line (see also Schreiber et al. 2010). I think an important implication of Figure 2.5 is that researchers studying MB in single and binary stars have a lot to learn from each other.

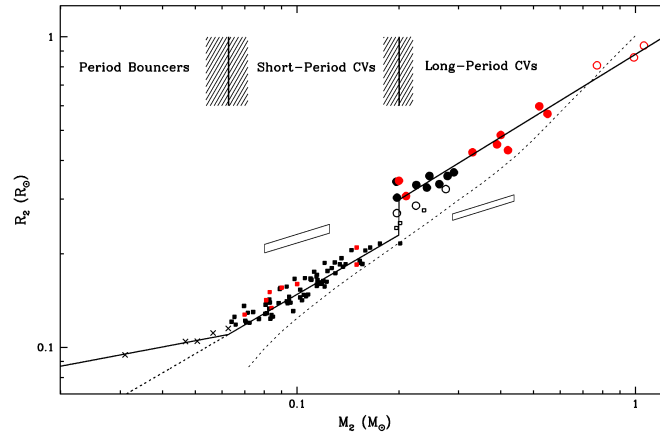


Figure 7. The mass-radius relation of CV donor stars, based on the data presented in Patterson et al. (2005). Superhumpers are shown in black, eclipsers in red. Filled squares (circles) correspond to short-period (long-period) CVs, crosses to likely period bouncers. The parallelograms illustrate typical errors. Open symbols correspond to systems in the period gap or likely evolved systems. The solid lines show the optimal broken power-law fit to the data. The dotted line is a theoretical mass-radius relation for MS stars (Baraffe et al. 1998). Figure reproduced and adapted from Knigge (2006).

3. Principles of CV Evolution: Observations

The standard “disrupted magnetic braking” model outlined above has been the cornerstone of CV evolution theory for almost three decades (Robinson et al. 1981; Rappaport et al. 1982, 1983; Spruit & Ritter 1983). It provides reasonable explanations for the existence of the period gap and the period minimum, but then this is what it was *designed* to do. Perhaps surprisingly, direct observational tests of other fundamental predictions it makes have only become possible over the last few years. Below, I will take a look at three key tests that have been carried out in this context. Here again, I will reproduce material from Knigge (2010), which provides a broader review of recent observational breakthroughs in CV research.

3.1. Disrupted Angular Momentum Loss at the Period Gap

It is remarkably difficult to test the idea that the gap is caused specifically by a disruption of AML – as opposed to, for example, the presence of distinct populations above and below the gap (e.g. Andronov et al. 2003). However, there is one key prediction of the model that can, in principle, be tested: if the standard model is correct, donors just above and below the gap should have identical masses, but different radii. After all, the donors above the gap have been significantly inflated by mass loss, while CVs below the gap have just emerged from a detached phase with their donors in thermal equilibrium.

In 2005, Joe Patterson showed for the first time that this fundamental prediction is correct (Patterson et al. 2005). Over almost two decades of painstaking work, he and his “Center for Backyard Astronomy” collaborators collected a vast amount of observational data on “superhumps” in CVs and showed that these observations can

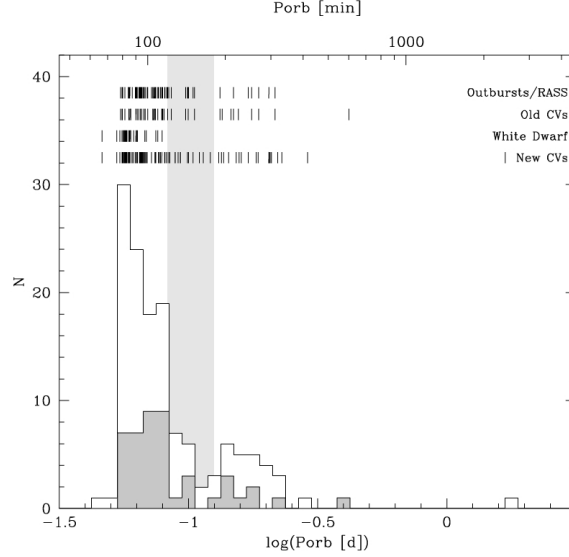


Figure 8. The period distribution of SDSS CVs, divided into 45 previously known systems (old SDSS CVs, grey) and 92 newly identified CVs (new SDSS CVs, white). Superimposed are tick marks indicating the individual orbital periods of the old and new SDSS CVs, those of SDSS CVs showing outbursts, those of SDSS CVs detected in the Rosat All-Sky Survey, and those of SDSS CVs which reveal the WD in their optical spectra. Figure adapted and reproduced from Gänsicke et al. (2009).

be calibrated to yield mass ratios for these systems. These mass ratios, in turn, can be used to obtain estimates of the corresponding donor masses and radii. He then combined these with similar estimates obtained for eclipsing CVs (such estimates are more precise, but available for far fewer systems) and put together the mass-radius relationship for CV donor stars shown in Figure 7.¹

The main result is immediately apparent: there is a clear discontinuity in donor radii at $M_2 \approx 0.2M_\odot$ that also cleanly separates long-period from short-period systems. In fact, donors in systems just below the period gap have radii consistent with ordinary MS stars of equal mass, while donors just above the gap have radii that are inflated by $\approx 30\%$. All of these findings are exactly in line with the basic predictions of the disrupted MB model.

Before moving on, it is worth emphasizing that Figure 7 alone cannot tell us the exact nature of the disruption in AML responsible for the period gap. In particular, *any* significant reduction of AML at $P \approx 3$ hrs will produce a period gap and a discontinuity in the donor mass-radius relationship. Without further modeling, the data cannot tell us if the AML above the gap has the strength expected for MB, nor if MB ceased completely or was merely somewhat suppressed at the upper gap edge. However, Figure 7 is extremely strong evidence for the basic idea of a disruption in AML at the upper gap edge.

¹Actually, the figure here is from Knigge (2006), but the data are based entirely on Patterson's compilation in Patterson et al. (2005).

3.2. The Period Spike: the Reversal of the Direction of Period Evolution at P_{min}

Another long-standing prediction of the basic evolution scenario for CVs is that there should be a “period spike” at the minimum period (e.g. Kolb & Baraffe 1999). More specifically, the orbital period distribution of any sufficiently deep sample should show at least a local maximum near P_{min} . This prediction is easy to understand: the number of CVs we should expect to find in any period interval is proportional to the time it takes a CV to cross this interval, $N(P) \propto \dot{P}^{-1}$. But $\dot{P}(P_{min}) = 0$, so the period interval including P_{min} should contain an unusually large number of systems. This is a critical prediction, since it follows directly from the idea that P_{min} marks a change in the direction of evolution for CVs.

Until recently, no CV sample or catalogue showed any sign of the expected period spike (e.g. Figure 3). However, CVs near P_{min} are very faint, so it was recognized that this could just be due to a lack of depth in these samples (Barker & Kolb 2003).

Enter the sample of ≈ 200 CVs constructed by Paula Szkody and collaborators from the Sloan Digital Sky Survey (SDSS; Szkody et al. 2002, 2003, 2004, 2005, 2006, 2007, 2009). This sample has a much deeper effective magnitude limit than previous ones and is therefore much more sensitive to the very faint CVs near and beyond P_{min} . However, in order to test for the existence of a period spike in this sample, precise orbital periods are needed. These were obtained via a long-term observational effort led by Boris Gänsicke (Gänsicke et al. 2009). Figure 8 shows the resulting period distribution for the SDSS CVs. The period spike near P_{min} is clearly visible.

Now, the existence of the period spike does not necessarily imply that the standard model is quantitatively correct. In particular, it does not mean that AML below the gap must be driven solely by GR. In fact, the location of the spike at $P_{min} \approx 82$ min is quite far from the prediction of the standard model ($P_{min} \approx 65 - 70$ min; e.g. Kolb 1993). Stronger-than-GR AML below the gap may be required to reconcile this discrepancy between theory and observations. However, the discovery of the period spike in the SDSS sample does provide convincing evidence for the fundamental prediction that CVs actually undergo a period *bounce* at P_{min} .

3.3. The Existence of CVs with Brown Dwarf Secondaries

A third key prediction of the standard model of CV evolution is that most CVs should already have evolved past the period minimum, i.e. they should be “post-period-minimum systems” or “period bouncers”. In fact, the standard model predicts that about 70% of present day CVs should be period bouncers, with all of these possessing sub-stellar donor stars (e.g. Kolb 1993). It was therefore quite disconcerting that, until recently, only a handful of *candidate* period bouncers were known. In particular, there was not even one CV with a well-determined donor mass below the Hydrogen-burning limit.

This situation has also changed for the better thanks to the SDSS CV sample. Crucially, this sample included several new *eclipsing* candidate period bouncers, for which component masses could be determined geometrically by careful modelling of high-quality eclipse observations.

Such eclipse analyses have been carried out by Stuart Littlefair and collaborators (Littlefair et al. 2006, 2008; Savoury et al. 2011) have so far yielded three significantly sub-stellar donor mass estimates, although one of these turns out to be a halo CV (which is interesting in its own right; Uthas et al. 2011). An example of a light curve and model fit for one of these systems – SDSS J1501, whose donor has a mass of $M_2 = 0.053 \pm 0.003 M_{\odot}$ – is shown in Figure 9.

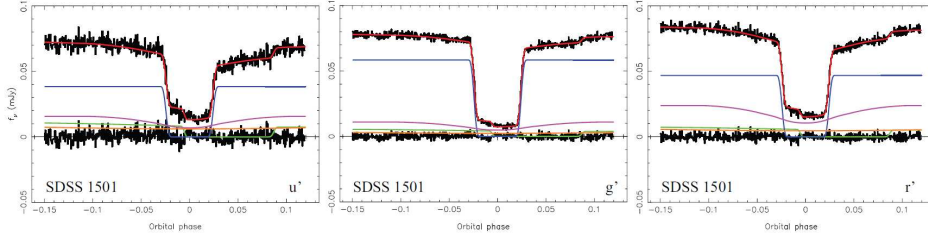


Figure 9. Model fits to the phase-folded u' , g' and r' light curves of SDSS J1501. The data (black) are shown with the fit (red) overlaid and the residuals plotted below (black). Below are the separate light curves of the WD (blue), bright spot (green), accretion disc (purple) and the secondary star (orange). Figure reproduced and adapted from Littlefair et al. (2008).

The definitive detection of CVs with sub-stellar donors does not prove that the standard model is correct – it is still far from clear, for example, whether there are enough of these systems in the Galaxy to be consistent with theoretical predictions. However, it does confirm the fundamental idea that (at least some) systems survive the stellar-to-substellar transition of their secondaries, while remaining active, mass-transferring CVs.

4. Reconstructing CV Evolution Empirically

The observational tests described above provide strong evidence that our basic ideas about CV evolution are at least qualitatively correct. But does the standard model agree *quantitatively* with observations? What is the strength of MB above the period gap? Is GR really the only AML mechanism acting below the gap? These issues are central not only to CVs, but to virtually all types of close binaries, since AML via MB and/or GR are thought to drive the evolution of these systems also.

Ideally, we would like to address such questions by reconstructing the evolutionary path followed by CVs empirically. In practice, this means that we want observations to tell us how the secular mass-transfer rate in CVs depends on orbital period. The word “secular” is key here, since it encapsulates the main difficulty in this project. The problem is that most conventional tracers of \dot{M} – in particular those tied to the accretion luminosity – are necessarily measures of the *instantaneous* mass transfer rate in the system. However, from an evolutionary perspective, what we need is the secular accretion rate, i.e. \dot{M} averaged over evolutionary time-scales. The trouble is that there is no guarantee that instantaneous and long-term \dot{M} are the same. In fact, it has been known for a long time that CVs with apparently very different instantaneous accretion rates (e.g. dwarf novae and nova-likes) can co-exist at the same orbital periods. One possible explanation is that CVs may undergo irradiation-driven mass-transfer cycles on time-scales of 10^5 yrs (the thermal time-scale of the donor’s envelope; e.g. Büning & Ritter 2004).

Recent years have seen the emergence of *two* new methods to overcome this problem. The first is based on the properties of the accreting WDs in CVs, the second on the properties of their mass-losing donors. The WD-based method builds on the theoretical work of Dean Townsley and Lars Bildsten, who have shown that the (quiescent) effec-

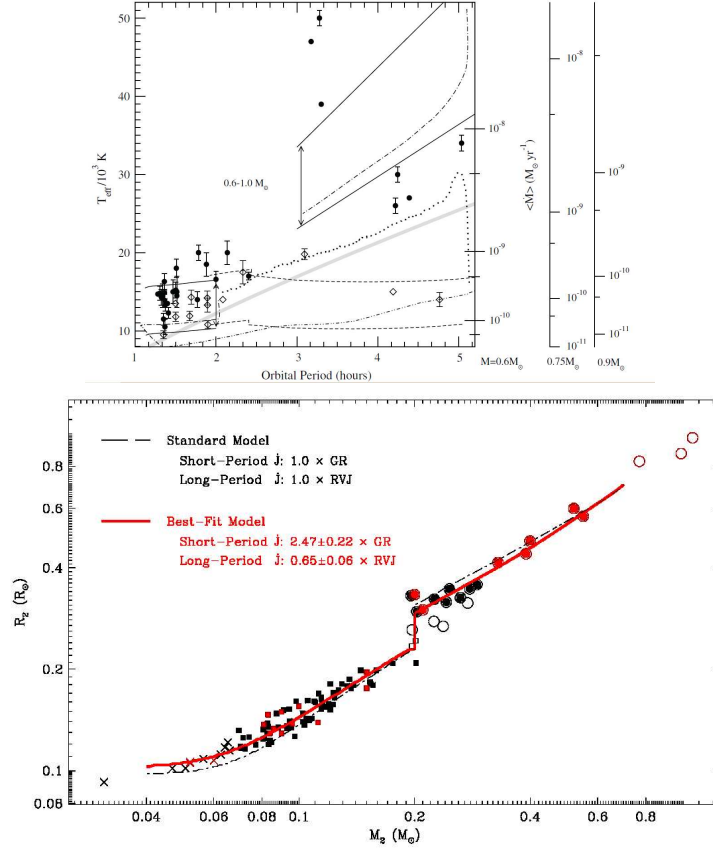


Figure 10. *Top Panel:* Reliable T_{eff} measurements for CVs. An approximate mapping to \dot{M} is shown on the right vertical scale assuming $M_{\text{WD}} = 0.75M_{\odot}$, $0.6M_{\odot}$, or $0.9M_{\odot}$. Several sets of predicted temperatures are also indicated: an empirical relation (Patterson 1984, thick gray line), traditional MB (Howell et al. 2001, dot-dashed line and between solid lines), two versions of reduced MB due to Andronov et al. (2003, dot-dot-dash line) and Ivanova & Taam (2003, dotted line), pure GR (between dashed lines). Figure reproduced from Townsley & Gänsicke (2009). *Bottom Panel:* Model fits to the observed CV donor mass-radius. The thin dashed line is the relationship predicted by the standard model, the thick solid line shows the optimal fit achieved by varying the strength of AML above and below the gap. Figure adapted from Knigge et al. (2011).

tive temperature of an accreting WD in a CV is a tracer of \dot{M} (Townsley & Bildsten 2002, 2003). The donor-based method, on the other hand, exploits the fact that CV secondaries are driven out of thermal equilibrium, and hence inflated, by mass loss (see Figure 7). As discussed in detail in Knigge et al. (2011), this makes it possible to use the degree of donor inflation as a tracer of secular \dot{M} (see also Sirotkin & Kim 2010).

Both methods have their drawbacks, of course. WD-based \dot{M} estimates are sensitive to the masses of the WD and its accreted envelope (which are usually not well known), plus there remains a residual T_{eff} response to long-term \dot{M} variations, especially above the period gap. The main weaknesses of the donor-based method are its strong reliance on theoretical models of low-mass stars, as well as its sensitivity to apparent donor inflation unrelated to mass loss (e.g. due to tidal/rotational deformation, or simply as a result of model inadequacies).

The first results obtained by the two methods are shown in Figure 10. The left panel is taken from Townsley & Gänsicke (2009) and shows how $T_{eff}(P_{orb})$ predicted by different evolutionary models (including the standard one) compare to a carefully compiled set of observed WD temperatures. The right panel is adapted from Knigge et al. (2011) and shows a similar comparison between (standard and non-standard) models and data in the donor mass-radius plane.

A full discussion of these results would go far beyond the scope of this review, so I will focus on just one important aspect. Taken at face value, both methods seem to suggest that GR alone is not sufficient to drive the observed mass-loss rates below the period gap. However, much work remains to be done in testing these methods, exploring their limitations, verifying such findings and studying their implications. What is clear, however, is that we finally have the tools to test the standard model quantitatively and, if necessary, to derive an empirically-calibrated alternative model that can be used as a benchmark in population synthesis and other studies. In fact, the best-fit donor-based model in the right panel of Figure 10 is intended to provide exactly such an alternative (for details, see Knigge et al. 2011).

5. Summary and Conclusions

I hope this review has managed to get across that our understanding of CVs and their evolution has improved dramatically over the last few years. In particular, the long-standing fundamental predictions of evolution theory are finally being tested observationally. We have even learned to reconstruct CV evolution empirically, based on the properties of the primary and secondary stars in these systems.

Since the conference topic was on the topic of binary evolution, I have not talked much at all about the actual accretion process in CVs. However, here, too, there has been much progress in recent years. In my view way, one of the most significant developments in this area is the emerging recognition that virtually all facets of this process – including variability, disk winds and jets – are “universal”, with accreting WDs, neutron stars and black holes on all scales exhibiting quantitatively similar phenomenology (Knigge 2010). In this context, CVs have the potential to become prime laboratories for the underlying accretion physics.

Acknowledgments. I am grateful to all of my many collaborators in the CV community over the years. Joe Patterson, Brian Warner, Isabelle Baraffe, Boris Gänsicke, Stuart Littlefair, Joe Patterson, Retha Pretorius and Brian Warner, in particular, have strongly influenced my thinking about CV evolution. This article was reprinted in part with permission from Knigge (2010; Copyright 2010, American Institute of Physics) and from Knigge (2011); Copyright 2011, Universal Academic Press).

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